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A dichotomy in radio jet orientations in elliptical galaxies

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Abstract. We have investigated the correlations between optical and radio isophotal position angles for 14302 SDSS galaxies with r magnitudes brighter than 18. All the galaxies are identified with extended FIRST radio sources. For passive early-type galaxies, which we distinguish from the others by using the colour, concentration and their principal components, we find a strong statistical alignment of the radio axes with the optical minor axes. Since the radio emission is driven by accretion on to a nuclear black hole we argue that the observed correlation gives new insight into the structure of elliptical galaxies, for example, whether or not the nuclear kinematics are decoupled from the rest of the galaxy. Our results imply that a significant fraction of the galaxies are oblate spheroids, perhaps rotationally supported, with their radio emission aligned with the stellar minor axis. Remarkably, the strength of the correlation of the radio major axis with the optical minor axis depends on radio loudness. Those objects with a low ratio of FIRST radio flux density to total stellar light show a strong minor axis correlation while the stronger radio sources do not. This split may reflect different formation histories and we suggest this may be a new manifestation of the better known dichotomy between slow rotating and fast rotating ellipticals.

1. Introduction

Searching for statistical alignments between radio and optical axes is motivated by the desire to find a connection between radio emission mechanism and the geometry of the host galaxy. Though there has been a long history of searching for such alignments, generally the results have been inconclusive (for example, Mackay (1971); Palimaka et al. (1979); Valtonen (1983); Birkinshaw & Davies (1985); Sansom et al. (1987)). In most investigations there appears to be a slight preponderance of objects where the radio elongation is more aligned with the optical minor axis than the major axis. The clearest result was obtained by Condon et al. (1991) who found that extended radio jets in 125 UGC galaxies were preferentially aligned with the optical minor axes of their hosts, with the effect being strongest for elliptical galaxies. Recent work indicates that elliptical galaxies have complex kinematics. These include decoupled cores in a significant fraction of galaxies (for example, Halliday et al. (2001); Loubser et al. (2008); Krajnović et al. (2008)), and the separation of such galaxies into two distinct classes, cored on non-cored (Kormendy et al. (2009)) and/or fast and slow rotators (Emsellem et al. (2000)). Therefore studying the alignment between the stellar population and the radio emission assumes added significance.

All the historic results have been based on relatively small numbers of objects (~ 100) but with the advent of deep radio and optical surveys like FIRST (Becker et al. (1995)) and the SDSS (York et al. (2000)), respectively, it is pos-

sible to construct samples with orders of magnitude larger numbers. But going deeper in radio flux density means that the galaxies identified with the radio sources are no longer dominated by the ellipticals, which were the targets of early studies, but are now a mixture of ellipticals and disk-dominated star-forming galaxies. Since the source of the emission is fundamentally different in the two types of galaxy one might well expect their alignment properties also to be different. Hence we need to distinguish reliably between early- and late-type galaxies and we do this by using SDSS photometry. In this paper we will focus almost exclusively on radio sources hosted by elliptical galaxies.

2. Sample selection

We use optical identifications of FIRST radio sources listed in the SDSS DR6 database (Adelman-McCarthy et al. (2008)) which were selected using the procedure defined in Ivezić et al. (2002). There are 239993 such identifications. We have also extracted the photometric magnitudes from SDSS (*ugriz*), the integrated flux density measured by FIRST (S_{int}), the position angle (PA, α) computed from the isophotal distribution in the *r*-band by SDSS along with the equivalent from FIRST, the major (*a*) and minor (*b*) axes measured by SDSS and FIRST, and R_{50} and R_{90} measured from the Petrosian intensity profile model fitted to the SDSS images (Petrosian (1976)). We also use the concentration $c = R_{90}/R_{50}$ to help distinguish elliptical galaxies from the others; for small c the light distribution has an exponential profile and fits the profile of a disk galaxy, whereas for large values of c the profile is approximated by a de Vaucouleurs profile which fits the light distribution of an elliptical galaxy.

For our investigation we require galaxies and radio sources for which there are reliable measures of the PAs of extended emission. Since it is difficult to compute the PA accurately for very faint galaxies and very round ones, we have excluded all galaxies with $r > 18$, $b/a > 0.8$ in either SDSS or FIRST, and those with $a < 2''$ in FIRST (since FIRST has a $5''$ beam). This leaves a total of 14302 galaxies. We further split the sample based on photometric determined parameters. It has been shown by Strateva et al. (2001) that the colour defined by $u - r$ can discriminate between different distributions in the bimodal $g - r$ vs. $u - g$ colour-colour diagram for an earlier SDSS data release. The colour and concentration are known to be correlated (see for example, Strateva et al. (2001)). There is a bimodality in the density of points in the colour-colour diagram for our sample, suggesting that there are indeed two populations, with the redder, more highly concentrated objects being the elliptical galaxies. In order to investigate this quantitatively we have performed a principal component analysis (PCA) on the sample, initially with two variables $u - r$ and c . The two components which are generated by this procedure are

$$\begin{aligned} C_1 &= 0.965c - 0.262(u - r), \\ C_2 &= 0.262c + 0.965(u - r). \end{aligned} \tag{1}$$

Dividing at $C_2 = 3.5$ gives a near optimum separation of the two types of galaxy.

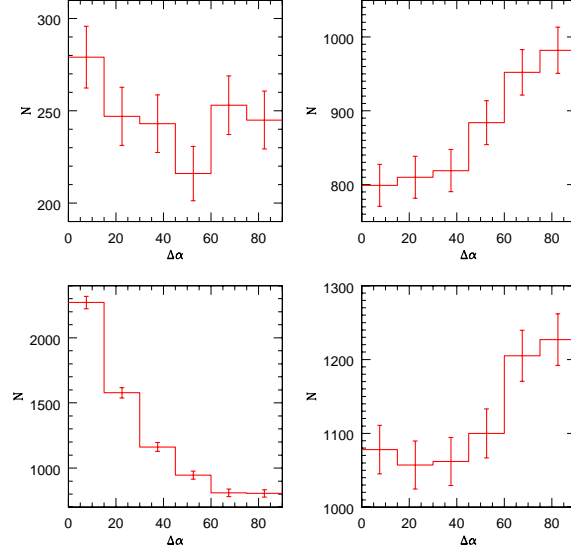


Figure 1. Splits of the data on the basis of PCA and axial ratio. The distributions are: $C_2 < 3.5$ (bottom left), $C_2 > 3.5$ (bottom right), $C_2 > 3.5$ and $b/a < 0.6$ (top left) and $C_2 > 3.5$ and $b/a > 0.6$ (top right)

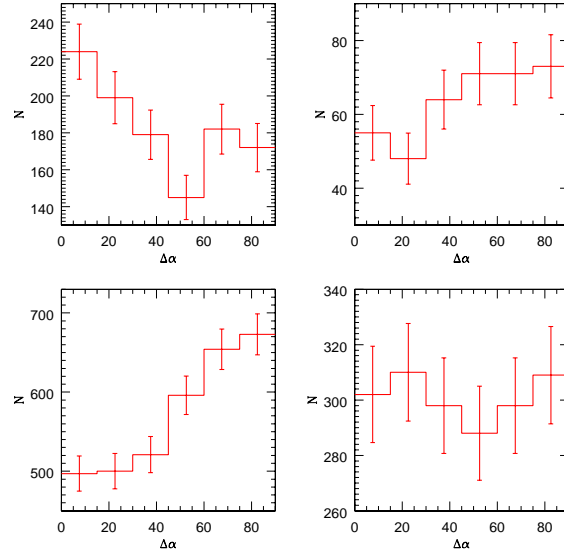


Figure 2. Histograms for the case $C_2 > 3.5$ with various splits based on b/a and $t - r$. The two plots at the bottom have $b/a > 0.6$ and the two the top have $b/a < 0.6$. The two on the left are radio-quiet with $t - r > -2.5$ and the two on the right are radio-loud with $t - r < -2.5$.

3. Results

In Fig. 1 we show the distribution of $\Delta\alpha$ split by principal component C_2 and by axial ratio b/a . As expected the two types of galaxy behave differently. It is very evident that the blue, less concentrated galaxies ($C_2 < 3.5$), which broadly represent the disk-dominated, spiral population, have the optical and radio major axes correlated, whereas the red, highly concentrated galaxies ($C_2 > 3.5$), which are part of the elliptical population, have a correlation between the optical major and radio minor axes. The most statistically significant minor axis alignment is obtained for a sub-sample defined by $C_2 > 3.5$ and $b/a > 0.6$. We draw attention to the fact that we are dealing with relatively round galaxies. Though the major axis alignment for the spiral galaxies is interesting in its own right, for the rest of this contribution we will concentrate our discussion on the early-type galaxies. An extensive discussion of the behaviour of both types of galaxy can be found in Battye & Browne (2009).

The bias towards $\Delta\alpha = 90^\circ$ in the red objects with high concentrations is highly statistically significant. Since in these predominantly elliptical galaxies the radio-emission is almost certainly powered by mass accretion on to a central disk/black hole system, the radio elongation we measure will be that of the overall spin axis of that system. Our results confirm those reported by Condon et al. (1991) who saw a strong trend for the jet axes in UGC elliptical galaxies to be aligned with the optical minor axes. Simulations done by Sansom et al. (1987) for different galaxy geometries show that strong minor axis alignments are observable only for galaxies which are oblate spheroids. Therefore our results imply that there is a bias for the spin axis of the central engine to be aligned with the minor axes of galaxies and also that these galaxies are predominantly oblate spheroids, something supported by the analysis of galaxy shapes (Padilla & Strauss (2008)). The radio minor axis alignment is something one might expect to see if the galaxies were rotationally supported and the black hole accretion disk axes were aligned with the overall galaxy rotation axes. One should contrast what we see here in elliptical galaxies with that seen in Seyfert galaxies where there is only a weak relationship between jet axis and the axis of the host galaxy disk (Kinney et al. (2000); Gallimore et al. (2006); Raban et al. (2009)).

We have divided the sample further by the ratio of radio to optical flux density expressed as $t - r$ where r is the r magnitude and t is given by:

$$t = -2.5 \log_{10} \left(\frac{S_{\text{int}}}{3631 \text{Jy}} \right). \quad (2)$$

What is most remarkable is that the strong $\Delta\alpha = 90^\circ$ bias in the elliptical galaxies is confined to the radio quieter subset of these objects as is clearly evident from Fig.2 The division at $t - r = -2.5$ produces sub-samples with a ratio in numbers of around 2:1 and was not chosen *a priori* to have any particular physical significance for the elliptical galaxy population. However, the division seems to have physical significance, indicating that there are two distinct types of object within the elliptical population exhibiting quite different behaviour. We speculate that the galaxy shape in the quieter objects is fixed by rotation and that jets emerge along the stellar rotation axis. We emphasize that the two radio populations we talk about here have nothing to do with the traditional

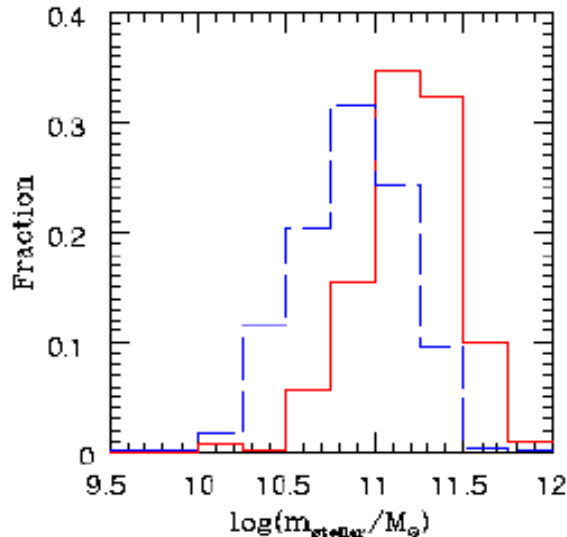


Figure 3. Plot of the stellar masses of the sample split by the ratio of radio to optical luminosity. The lower luminosity objects are indicated by the dashed line and the higher by the continuous line.

FR1/FR2 radio morphological division that for an L^* galaxy occurs at around $t - r = -7$ not $t - r = -2.5$. Virtually all our galaxies are in the FR1 range.

4. Discussion; two varieties of elliptical galaxies

We find that amongst the radio quieter objects the radio emission is strongly aligned with the optical minor axes. This requires there to be negligible projection effects suggesting that the galaxies are oblate, and possibly rotationally supported, with the jet emerging along the rotation axis. Amongst the radio louder objects there is no preferred radio-optical alignment, more akin to what we would expect if the host galaxies were triaxial and not rotationally supported. We suggest that this dichotomy in alignment behaviour is another manifestation of the primarily optical dichotomy which exists between giant ellipticals and normal (and dwarf) ellipticals (see for example Faber et al., 1997; Kormendy et al. 2008). The former galaxies have cores, are slowly rotating and triaxial, and generally have boxy isophotes, while the latter are coreless, are rapid rotators and oblate, and generally have disk isophotes. Assuming our association of the two dichotomies is correct, a surprising consequence is that the distinction in terms of mass between “giant” and “normal” elliptical galaxies for the subset with radio emission appears to be very modest. In Fig.3 we show distributions of stellar masses for the two subsets. The radio quieter objects are indeed less massive but only by around a factor of two. Given that the observed ratio of radio to stellar luminosity ($t - r$) spans more than three orders of magnitude, it is instructive to think in terms of the efficiency with which the different types of

galaxy produce radio emission for a given stellar mass. From this viewpoint the isotropic, rotationally supported galaxies are low efficiency radio emitters while the anisotropic, slow rotators, have relatively high radio efficiencies. Getting the gas from stellar mass loss to where it can be accreted by the black hole is an obvious candidate that can affect the efficiency. Alternatively, the black hole spin, which may relate to the formation history of the galaxy, could affect the efficiency with which accreted fuel is converted into radio emitting jets.

5. Summary

We find a highly statistically significant tendency for the axis of the radio emission to align with the minor axis of the starlight in elliptical galaxies. Surprisingly, this trend is confined to the less radio-luminous objects. We suggest that this result may be a new manifestation of the well known dichotomy in the optical properties of elliptical galaxies; i.e. between those with cores and which are slow rotators and those without cores and which are rotationally supported.

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